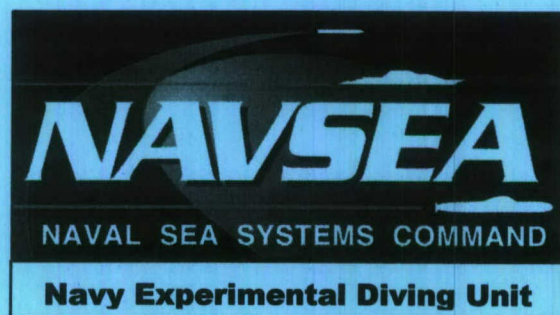


**Navy Experimental Diving Unit
321 Bullfinch Rd.
Panama City, FL 32407-7015**

**TA 06-19
NEDU TR 07-15
OCTOBER 2007**

**PULMONARY EFFECTS OF EIGHT-HOUR
MK 16 MOD 1 DIVES**



Author: B. Shykoff, Ph.D.

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20080506223

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE				
1a. REPORT SECURITY CLASSIFICATION Unclassified		1b. RESTRICTIVE MARKINGS		
2a. SECURITY CLASSIFICATION AUTHORITY		3. DISTRIBUTION/AVAILABILITY OF REPORT		
2b. DECLASSIFICATION/DOWNGRADING AUTHORITY		DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited.		
4. PERFORMING ORGANIZATION REPORT NUMBER(S) NEDU Technical Report No. 07-15		5. MONITORING ORGANIZATION REPORT NUMBER(S)		
6a. NAME OF PERFORMING ORGANIZATION Navy Experimental Diving Unit	6b. OFFICE SYMBOL (If Applicable)	7a. NAME OF MONITORING ORGANIZATION		
6c. ADDRESS (City, State, and ZIP Code) 321 Bullfinch Road, Panama City, FL 32407-7015		7b. ADDRESS (City, State, and Zip Code)		
8a. NAME OF FUNDING SPONSORING ORGANIZATION NAVSEA N873	8b. OFFICE SYMBOL (If Applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER		
8c. ADDRESS (City, State, and ZIP Code) CNO N873, Deep Submergence, Chief of Naval Operations, Submarine Warfare Division, 2000 Navy Pentagon, PT-4000, Washington, DC 20350		10. SOURCE OF FUNDING NUMBERS		
		PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO. 06-19 WORK UNIT ACCESSION NO.
11. TITLE (Include Security Classification) (U) Pulmonary Effects of Eight-hour MK 16 MOD 1 Dives				
12. PERSONAL AUTHOR(S) B. Shykoff, Ph.D.				
13a. TYPE OF REPORT Technical Report	13b. TIME COVERED Aug 2007	14. DATE OF REPORT October 2007		15. PAGE COUNT 10
16. SUPPLEMENTARY NOTATION				
17. COSATI CODES		18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB-GROUP		
		Nitrox diving, Pulmonary oxygen toxicity, FVC, D _L CO, FEV ₁ , diffusing capacity, 1.3 atm, pulmonary function, 8-hour dives, MK 16		
19. ABSTRACT: Most conclusions that we have reached about pulmonary oxygen toxicity at an oxygen partial pressure of 1.3 atm have been obtained from shallow dives with 100% oxygen. To confirm that results are valid for the MK 16 MOD 1, we compared effects of 8-hour dives at a depth of 50 feet (50% oxygen) to those previously attained at 12 to 14 feet. Seventeen U.S. Navy divers dove underwater in the ascent tower at Navy Diving and Salvage Training Center with the MK 16 MOD 1 underwater breathing apparatus. Dives were 8-hours long. Divers were resting, and were allowed air breaks of no more than 10 minutes each and no more than 35 minutes overall to replenish the UBAs and to eat and drink. Pulmonary function and respiratory symptoms were assessed before and after diving and were compared to previous results. Across all postdive days, ten subjects reported symptoms, ten showed depressed pulmonary function, and five had both. In no time interval were the incidences different from those after similar 100% oxygen dives. Absorption atelectasis is not important in the etiology of pulmonary oxygen toxicity of diving, and results obtained with 100% oxygen are applicable to the MK 16 MOD 1.				
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT <input type="checkbox"/> UNCLASSIFIED/UNLIMITED <input checked="" type="checkbox"/> SAME AS RPT. DTIC USERS		21. ABSTRACT SECURITY CLASSIFICATION Unclassified		
22a. NAME OF RESPONSIBLE INDIVIDUAL NEDU Librarian	22b. TELEPHONE (Include Area Code) 850-230-3100	22c. OFFICE SYMBOL 03		

DD Form 1473

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INTRODUCTION

Divers using MK 16 MOD 1 underwater breathing apparatus (UBA) at depths greater than 33 feet of seawater (fsw) breathe gas with variable nitrogen fractions and constant PO_2 . Although the hypothesis has been that the toxic effects of oxygen result from elevated PO_2 rather than from elevated oxygen fraction, an alternative is that toxic effects decrease with increasing concentrations of diluent gas because the inert component prevents collapse of slowly ventilated alveolar regions. We tested these hypotheses by comparing pulmonary function and respiratory symptoms after MK 16 MOD 1 dives to 50 fsw with those from shallower dives with the same PO_2 , some with 100% oxygen at about 13 fsw, and some with 84% oxygen at 20 fsw.¹ If PO_2 alone determines toxicity, the limits derived with 100% oxygen apply directly to MK 16 MOD 1 diving, but if diluent is protective, the limits may be overly conservative.

The incidence of pulmonary toxic effects with short underwater exposures to 100% oxygen is low, and direct testing of operational durations would require an extremely large number of dives. Although operational dives will not be eight hours long, the incidence of mild pulmonary oxygen toxicity after eight-hour dives with 100% oxygen is relatively high: of 23 divers, 22% reported symptoms during the dive, 43% after surfacing, and 35% on a later day.¹ As many fewer eight-hour than shorter duration dives were needed to answer our question, we chose eight-hour dives for testing.

We measured changes in pulmonary function and assessed symptoms immediately and for several days after diving exposures. The pulmonary function variables determined from forced flow-volume loops were forced vital capacity (FVC), forced expired volume in one second (FEV_1), peak expired flow or maximum forced expired flow (FEF_{max}), and average forced expiratory flow from 25% to 75% of expired volume (FEF_{25-75}). Diffusing capacity of the lung for carbon monoxide (D_LCO) was determined from single breath tests. The lower limits of normal for pulmonary function variables were defined as the lower 95% confidence bands for each variable found for the Navy Experimental Diving Unit (NEDU) population: namely, -7.7% for FVC, -8.4% for FEV_1 , -16.8% for FEF_{max} , -17.0% for FEF_{25-75} , and -14.2% for D_LCO .²

METHODS

GENERAL

Seventeen U.S. Navy divers from NEDU and NEDU Reserve Unit Great Lakes participated in the dives. The protocol was reviewed and approved by the Institutional Review Board at NEDU, and all divers gave written informed consent.

Before participating, any diver who had not used the MK 16 UBA within the previous six months underwent a short familiarization dive directed by a MK 16 supervisor from NEDU. Dives were conducted at a depth of 50 feet of fresh water in the buddy breathing ascent tower (BBAT) at Navy Diving and Salvage Center (NDSTC), Panama City, FL, under the supervision of a MK 16 supervisor and a Master Diver from NEDU and a BBAT diving supervisor from NDSTC. The water temperature was between 85 °F and

88 °F, and divers wore wet suits. At 50 fsw and PO₂ 1.3 atm, divers breathed approximately 50% oxygen in nitrogen and incurred no decompression obligation; the air equivalent depth was 18 fsw.³

Because the nominal canister duration for the MK 16 is 300 min, divers surfaced and changed UBAs after approximately four hours. Divers had additional surface intervals at any time they became necessary for UBA maintenance and after two and six hours of diving to eat and drink, but no single air break exceeded ten minutes, and the total air-break time was limited to no more than 35 minutes during eight hours.

For one week before the study, subjects had not been exposed to PO₂ greater than 1.2 atm except in the familiarization dives, and for two days prior they had not performed any dive except the familiarization dive. They refrained from other diving until pulmonary function testing was complete. Each subject's smoking behavior and history of respiratory allergies were noted, and subjects' general health and use of medications also were recorded during the studies. All subjects were in good health.

Table 1.
Subject characteristics

n = 17	Median (range)
Age (Yr)	35 (25–49)
Height (in)	70 (62–73)
Weight (lb)	185 (155–235)
Smokers (#):	<i>never, 9; former, 7; occasional, 1</i>
Respiratory allergies, pollen or other (#):	1 (not allergy season)
Medication use (#):	Anti-inflammatory: 1

To measure pulmonary function, at each session we acquired three flow-volume loops performed and repeatable according to American Thoracic Society standards.⁴ FVC, FEV₁, FEF_{max}, and other variables were read from the flow-volume loops. The sessions also included three single-breath D_LCO measurements made with a 10-second breath hold. The variables used to obtain D_LCO were calculated from the gas concentrations before and after the breath hold. Adjustments were made for carboxyhemoglobin and hemoglobin concentrations,⁵ and the samples were chosen to ensure that the analyzer signal was stable when measurements were recorded.⁶

Baseline pulmonary function tests (PFTs) were done within the week before the test dives. Flow-volume tests were generally measured again within the week before diving. The averages of three technically correct diffusing capacity tests and of three properly performed flow-volume loops from each session were used for comparisons with later values. Both flow-volume curves and diffusing capacities were measured within two hours of surfacing and for three days after the dive, Days +1 to +3 or Days +1, +2, and +5 for some Wednesday dives.

Visual refraction was measured at each session measuring pulmonary function.

Divers were questioned about specific symptoms (Table 2) each hour during the dive and at each session measuring pulmonary function.

Table 2.
Symptoms list

During the dives:	After the dives:
Vision changes	Visual complaints
Ringling or roaring in ears	Ear problems
Nausea	
Tingling or twitching	Unreasonable fatigue
Light-headedness or dizziness	Reduced exercise tolerance
Chest tightness	Chest pain or tightness
Shortness of breath	Shortness of breath
Rapid shallow breathing	
Inspiratory burning	Inspiratory burning
Cough	Cough

EXPERIMENTAL DESIGN AND ANALYSIS

Confidence in estimates of the incidence of changes in pulmonary function or of symptoms with $\alpha = 0.1$ (90% confidence in the proportion) was obtained from the binomial distribution.

EQUIPMENT AND INSTRUMENTATION

The Collins CPL Pulmonary Function Testing System instruments (Ferraris Respiratory; Louisville, CO) were used to measure pulmonary function. The test gas used to measure D_LCO contained 0.3% CO and 0.3% methane. A CO oximeter (Instrumentation Laboratory; Lexington, MA) determined the pretest carboxyhemoglobin and hemoglobin concentrations from a venous blood sample. An autorefractor (Humphrey model 599, Carl Zeiss Meditec; Dublin, CA) was used to measure visual refraction.

Divers used KMS 48 masks and MK 16 MOD 1 UBAs with oxygen bottles charged to 2400 to 3000 psig. Diluent was 79/21 N_2O_2 . Canisters were filled with 8-12 Sofnolime (O.C. Lugo, NJ) according to standard NEDU procedures. Projected canister duration was 300 minutes, and projected bottle duration was 316 minutes.³

Two emergency gas supplies, consisting of second-stage regulators and mouthpieces hanging on hoses at least 50 feet in length attached to scuba bottles on the surface, were hung into the tower. Neither was used during the protocol.

PROCEDURES

Four or five divers took part in each dive. In the morning, divers reported to the BBAT, where, under direction of the dive supervisor, they donned equipment, entered the water, and were directed to descend. After diving, the subjects were escorted to NEDU for blood draws, testing of pulmonary function and visual refraction, and recording of symptoms. On the days after diving, the laboratory measurements were repeated.

RESULTS

PULMONARY FUNCTION AND RESPIRATORY SYMPTOMS

Incidences of symptoms and signs

Immediately after surfacing, seven subjects reported symptoms and five demonstrated reduced pulmonary function. On the following days, four divers, one of whom had been without symptoms earlier, had respiratory symptoms, and nine — four without previous measurable changes — showed decreased pulmonary function. Two subjects had moderate symptoms at some time, but other reports were of mild symptoms.

Table 3 lists the incidences of symptoms and changes in pulmonary function variables from 50 fsw and shallow eight-hour dives with $PO_2 = 1.3$ atm. Binomial confidence intervals overlap for all of these conditions. Details of the symptoms and changes in pulmonary function related to the 50 fsw dives are listed in Table 4.

Table 3.

Comparison of 50 fsw MK 16 dives with shallow 100% oxygen dives

		50 fsw MK 16	Shallow 100% O ₂ ¹
Symptoms	During	12%	22%
	On surfacing	41%	43%
	Later day	24%	35%
Decreased PFT	On surfacing	29%	13%
	Day +1	41%	21%
	Day +2	13%	13%
	Day +3	13%	4%

Other effects

Two divers reported irritability after diving. No divers showed any significant change in visual refraction after these dives. Despite the breaks at which food and water were consumed, five subjects showed postdive dehydration sufficient to increase hemoglobin concentration by more than 10%. Only three divers (18%; 95% CI 6–41%) reported fullness and crackling in the ears on the day after the 50 fsw dives, as compared to nine of 23 divers (39%) after 100% oxygen dives,¹ but small numbers mean that this result is not significantly different.

Table 4.

Respiratory symptoms and decreases in pulmonary function during and after dives

Diver	During (hour)	Postdive	Day +1	Day +2	Day +3 or +5
1	-	FVC -9.4% FEV ₁ -14.9% FEF _{mid} -26.5% c	FEV ₁ -9.5% FEF _{mid} -22.7% c	FEV ₁ -8.7% FEF _{mid} -23.2% c	FEF _{mid} -19.0%
2	-	c, i	-	-	-
3	-	i, t	e	-	-
4	-	c	c	c, i, t	c, d, i, t
5	-	c, d	FEV ₁ -12.0% FEF _{mid} -29.5%	-	-
6	i (6), i(7,8)	i	-	-	-
7	-	FVC -9.3% D _L CO -22.0%	FVC -11.4% FEV ₁ -10.7% d, e, i, t	d, e, t	-
8	-	FVC -10.2% FEV ₁ -10.3%	FEV ₁ -20.2% FEF _{max} -33.1% FEF _{mid} -32.0% c	-	-
9	-	-	FVC -8.1% FEV ₁ -10.0% FEF _{mid} -17.2% e	-	-
10	i (4-8), t (7)	d, i, t	-	-	-
11	-	-	FEV ₁ -8.4%	-	-
12	-	-	-	FEF _{max} -19.1%	-
13	-	D _L CO -18.1%	D _L CO -19.3%	Lost to follow-up	
14	-	FVC -10.1%			
15	-	-	-	t	FEV ₁ -10.0% FEF _{mid} -19.4%
16, 17	No signs or symptoms				

Diver numbers are arbitrary and not linked to those in other reports.

Abbreviations: "c" is cough, "d" is dyspnea (shortness of breath), "e" is exercise intolerance, "i" is inspiratory burning, and "t" is chest pain or tightness. Roman face indicates mild, and **bold**, moderate symptoms. FEF_{mid} means FEF₂₅₋₇₅.

DISCUSSION

In eight-hour dives the presence of approximately 50% nitrogen in the breathing gas does not reduce pulmonary oxygen toxicity relative to 100% oxygen at the same partial pressure. The concept that pulmonary toxicity is related to chemical activity of oxygen rather than to absorption atelectasis is supported, and any pulmonary limits for $PO_2 = 1.3$ atm obtained with 100% oxygen should therefore apply to nitrox and heliox diving.

In anesthetized patients N_2 reduces or prevents postoperative absorption atelectasis, but the evidence on the amount needed is mixed: in one study, significantly less atelectasis was reported after 80% O_2 was used instead of 100% O_2 ;⁷ in another, 40% O_2 and a vital capacity maneuver were shown to prevent postoperative atelectasis,⁸ but in a different study, 30% O_2 and 80% O_2 showed equivalent and measurable atelectasis.¹⁹ Others have found evidence of atelectasis with a decrease in vital capacity after two hours of immersion during oxygen breathing.¹⁰ Our subjects in the 100% oxygen dives may have performed spontaneous reexpansion maneuvers like sighing or yawning. Alternatively, gas expansion during resurfacing, even from 13 fsw, may be sufficient to reopen closed alveoli, an event that would have happened every hour during air breaks in the previous study.¹

We had previously speculated that the larger number of delayed symptoms in those who dove with 100% O_2 than in those who dove with 84% gas could be related to prior atelectasis.¹ Unfortunately for that idea, on surfacing from the 50 fsw dives, so many divers showed evidence of pulmonary toxicity that it is difficult to comment on late-onset symptoms. We had also suggested that the reduced reporting of unreasonable fatigue after dives with 84% O_2 as compared to those with 100% O_2 might have been related to greater postatelectic inflammation in the second case.¹ While we did not record many complaints of fatigue, the definition of "unreasonable" probably was important here: divers expect to be tired after an 8-hour dive.

CONCLUSIONS

On the whole, the measurable effects of submersion for eight hours while breathing oxygen at a partial pressure of 1.3 atm were not different for 50% O_2 from what has previously been shown for 100% O_2 or for 84% O_2 . We confirm that eight-hour resting dives with $PO_2 = 1.3$ atm are indeed too long from a pulmonary standpoint, with 29% of subjects having both respiratory symptoms and at least one depressed pulmonary function variable at some time in conjunction with the dives, and with 59% demonstrating at least one of those adverse outcomes. More importantly, we establish that results obtained with 100% O_2 may reasonably be used for applications when the same PO_2 is to be obtained at greater depth with N_2 present in the breathing gas. PO_2 , not oxygen fraction, is the primary determinant of pulmonary oxygen toxicity in divers.

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